"Link" – the Smart Grid Paradigm for a Secure Decentralized Operation Architecture

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Abstract

This paper presents for the first time the Smart Grid Paradigm: the Link. Having a standardized structure, the Link can be applied to any partition of the power system: electricity production entity, storage entity, the grid or even the customer plant. From this paradigm are extracted three architecture components: the "Grid-Link", the "Producer-Link", and the "Storage-Link". The distributed Link-based architecture is designed. The new architecture allows a flat business structure across the electrical industry and minimizes the amount of the data, which needs to be exchanged. It takes also into account the electricity market rules and the rigorous cyber security and privacy requirements. The interfaces between the all three architecture components are defined. The power system operation processes like load-generation balance, dynamic security and demand response are outlined to demonstrate the architecture applicability. To complete the big picture, the operator role, the corresponding information and communication architecture and the market accommodation are also described.

Keywords

Demand response, Microgrids, Power system posturing processes, Smart grid, Smart grid architecture, Smart Grid Paradigm, Smart grid security, Technical functional architecture, Virtual Power Plants.

1. Introduction

The actual need for the integration of the distributed energy resources (DER) has brought onstage two main concepts: Virtual Power Plants (VPP) and Microgrids.

The VPP concept as an aggregation of a number of Distributed Generators (DG) was first introduced in the literature in 2001 [1, 2]. Soon it was found that adaptation must be made for the electric coupling of the VPP and above all the voltage and frequency performance, as well as the reliability aspects must be examined further [3]. As a result, many efforts have been made to improve the definition of the VPP concept, but this led to various definitions [4-7] instead of a single, unique one. Furthermore, the technical aspect of VPP is still in research process and the solution is not obvious [8].

Microgrid is another concept introduced as a solution for the integration of the DERs, including Energy Storage Systems (ESSs) and controllable loads [9, 10]. Similar to the VPP also the Microgrid concept is still under discussion in technical forums [11].

While both the VPP and Microgrid tray to offer a DER integration concept, they are not sufficiently broad to properly characterize the variety of the smart grid operation. No one of them can be adopted as a paradigm. As a result all architectures described based on the VPP, Microgrids or their combinations are very complex [12-17] and hardly practicable [18, 19].

The basic Cell Controller architecture [12] has a layered control hierarchy by using distributed agent technology. It defines three control modules: local, regional and enterprise, [13]. The Cell Controller architecture requires a tremendous amount of data to be exchanged between its modules. Similarly, an ultra large power system control architecture is presented in [14]. The central, multiple levels control framework is accompanied by a concept of vertical and horizontal distributed intelligence. [15] gives a hierarchical architecture for smart grids, which is based in seven major components like Grid, Region, Control Area, transmission substation, distribution substation, feeder, and consumers'. They have specialized agents who operate at different time scales. The prosumer-based layered architecture [16] put the prosumer as the major component, which consists of a combination of components like: energy sources, loads, storages and an electric grid. This architecture enables a “flat” business paradigm across the industry. The Smart Grid Architecture Model presented in [17] has six hierarchical levels, or zones, and five domains. The zones are: Process; Field; Station; Operation; Enterprise and Market while the domains are: Generation, Transmission, Distribution, distributed energy resources, DERs, and Customer Premises.

The smart grid of the future is generally characterized by more sensors, more communication, more computation, and more control, but a comprehensive conceptual architecture is seldom presented [18]. The concrete design of the future power system architecture is still a current topic [19].

In this paper is presented for the first time the smart grid paradigm: the “Link”, which it is used to present a comprehensive architecture. Three main components of the distributed Link-based architecture [20] are defined. The generalized component, the Grid-Link along with its types in the case of high-, medium-, low voltage grid, and customer plants are treated in details. The relevant electrical entities with the corresponding temporal availability, which should be exchanged via interfaces, are defined. The whole is accompanied by the analysis of different operation processes [21] like: load-production balance, n-1 security [22], static and dynamic stability [23, 24], etc. In the following the Link operator role and the transition period are discussed. The Link-architecture functionality is demonstrated by means of two power system posturing processes: demand response and dynamic security. The corresponding global ICT architecture and market accommodation are given. The applicability on the field is illustrated through the implementation of the medium voltage link in an industrial research project. Finally, the paper is completed by the proof of the data exchange minimization issue.

2. Power system overall model

The overall model “The Energy Supply Chain Net” [25], which is the base for the rise of the “Link” paradigm is defined as follows:

An “Energy Supply Chain Net” is a set of automated power grids, intended for “Chain Links” or “Links”, which fit into one an - other to establish a flexible and reliable electrical connection. Each individual “Link” or a “Link”-bundle operates independently and have contractual arrangements with other relevant boundary “Links”, “Link”-bundles, and suppliers which inject directly to their own grid. Each “Link” or “Link”-bundle is communicatively coupled with the other relevant “Links” or “Link”-bundle’s via the usual communication instruments.

In terms of the network operation and construction characteristics, the electric power grid is divided into two parts: transmission (which includes the high voltage grid, HVG) and distribution (which includes the medium voltage grid, MVG and the low voltage grid, LVG). Each customer plant has its own grid, CPG, which directly supplies the loads as well. Fig. 1 shows an overview of the power grid according to “The Energy Supply Chain Net” model. HVG, MVG, LVG and CPG are presented through ellipse plots. The primary and secondary control loop is represented by lines, while the respective control area for the secondary control is depicted through hatched surfaces. Here it should be noted that each of the grid parts has the same control scheme. Therefore not only the HVG, but also MVG, LVG and CPG are also designed to have primary and secondary control for both major quantities frequency and voltage. Thus, the power system is conceived as an “Energy Supply Chain Net” with each grid part (HVG/MVG/LVG and CPG) being considered as a Link on its own.

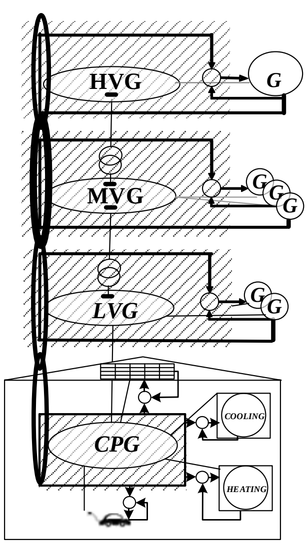

Fig. 1. Overview of the power grid according to “The Energy Supply Chain Net”.

3. Technical-Functional Link Architecture

The "Energy Supply Chain Net" is an approach to model objectives and functions of complex power system processes, which involves interactions between the power flows, the information and the market. To present and characterize the complex smart grid processes the "Link" paradigm is derived as follows.

3.1. The Link-paradigm

Fig. 2 shows an overview of the "Link"-paradigm, the deduced architecture components and the resulting link based architecture. The *Link-paradigm is* defined as *a composition of an electrical appliance (be a grid part, producer or storage), the corresponding controlling schema and the Link interface,* Fig 2a. Based on the "Link"-paradigm there are defined three main architecture components:

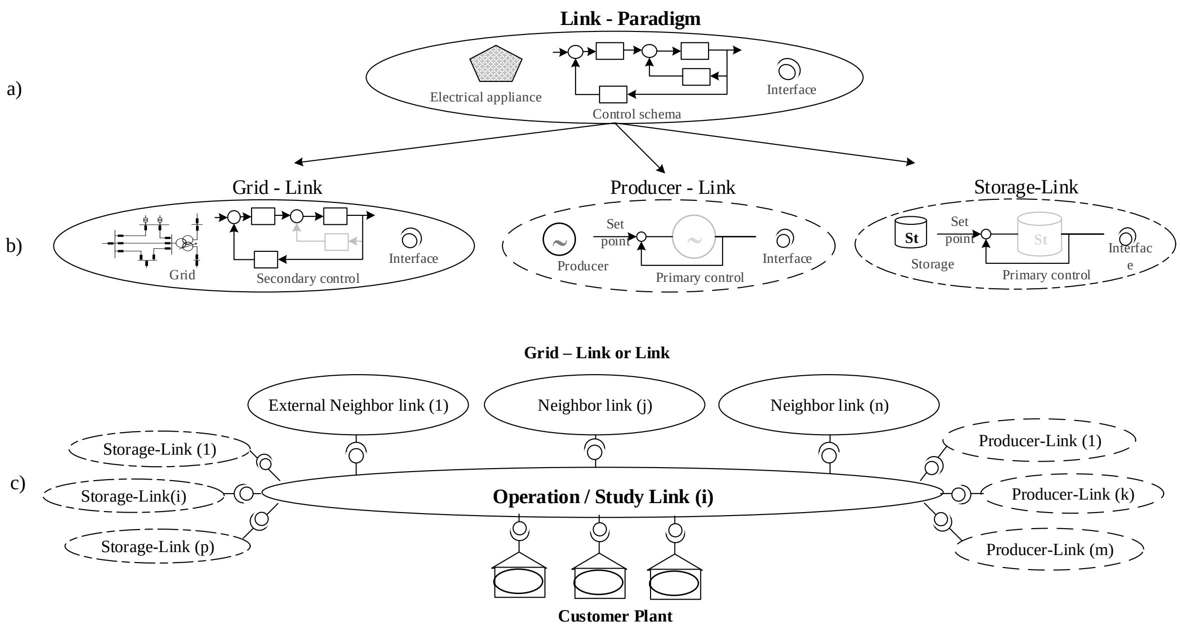

Fig. 2. An overview of a) the Link-paradigm, b) the deduced architecture components and c) the resulting link based architecture.

"*Grid-Link*"; the "*Producer–Link*" and the "*Storage-Link*", Fig. 2b.

<u>The Grid-Link / the Link</u>

For a simple and understandable presentation in the following will be used the term Link instead of Grid-Link.

The *Link is* defined as *a composition of a grid part, called Link_Grid, with the corresponding Secondary-Control and the Link_Interfaces.*

The *Link_Grid size* is variable and *is defined from the area, where the Secondary-Control is set up.* Thus the Link_Grid may include for e.g. one subsystem (the supplying transformer and the feeders supplied from it) or a part of the sub-transmission network, as long as the secondary control is set up on the respective area. As a result, depending on its size the Link may represent a Microgrid [11], nanogrid [26] or even a large high voltage grid.

Fig. 3a shows a typical Link_Grid overview. The *Link_Grid* refers to *electrical equipment like lines/cables, transformers and reactive power devices, which are connected directly to each other by forming an electrical unity*. Each Link-grid has a number of boundary nodes through which it is connected with other neighbor Links (Boundary Link Node, BLiN), Producer-Links injecting directly into it (Boundary Producer Node, BPN), Storage-Links connected directly into the Link-grid (Boundary Storage Node, BSN) and loads supplied from it (Boundary Load Node, BLoN).

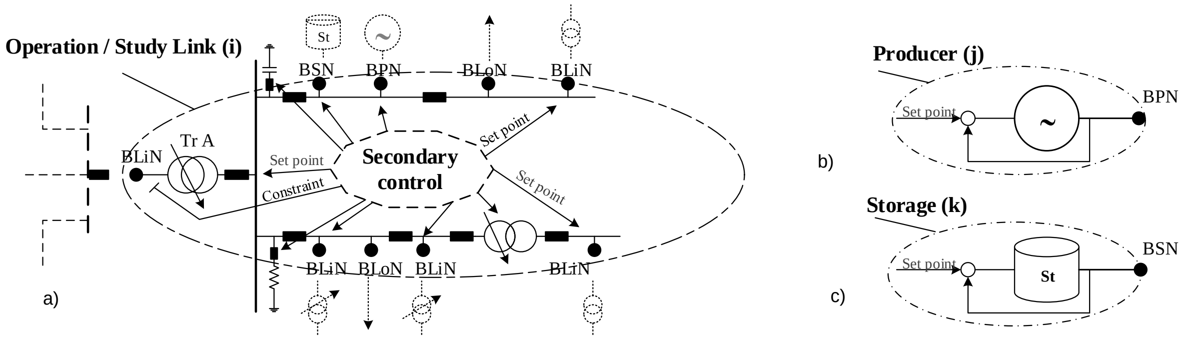

Fig. 3. Detailed representation of the architecture components: a) the Link; b) the Producer; c) the Storage.

As per definition, the Link-grid is upgraded with secondary control for both major entities of power systems frequency and voltage. Its algorithm needs to fulfill technical issues and calculate the set points by respecting the dynamic constraints which are necessary to enable a stable operation. Actually, the Link-grid own facilities, transformers and the reactive power devices are almost upgraded with primary/local control. Thus the secondary control will send set points to own facilities and to all entities connected at the boundary nodes.

The Producer-Link / the Producer

For a simple and understandable presentation in the following will be used the term Producer instead of Producer-Link.

The *Producer* is defined as *a composition of an electricity production facility be a generator, photovoltaic, etc., its Primary-Control and the Producer_Interface.*

Fig. 3b shows a typical Producer overview. Each Producer has a boundary node BPN through which it is connected with the Link_Grid where it is injecting the electricity.

The Storage-Link / the Storage

For a simple and understandable presentation in the following will be used the term Storage instead of Storage-Link.

The *Storage* is defined as *a composition of a storage facility be the generator of a pump power plant, batteries, etc., its Primary-Control and the Storage_Interface.*

Fig. 3c shows a typical Storage overview. Each Storage has one boundary node BSN through which it is connected to the Link_Grid.

The Link-based architecture

The data privacy and the big data transfer are the two biggest challenges which the smart grids technologies are facing today. To overcome these two challenges, i.e. to guarantee the data privacy and to minimize the number of relevant data which need to be exchanged, the distributed Link based architecture [20] is chosen. Fig. 2c shows the Link based architecture. The key principle of this design is to prohibit access to all resources by default, allowing access only through well-defined boundary points, i.e. interfaces. As already mentioned previously, the Link-grid, which is also the study and/or the operation object, has a number of boundary nodes through which the neighbor Links, Producers, Storages and loads are connected. They are usually electrically connected with other Links via switches (circuit breakers, switches or fuses). To ensure a stable and reliable operation of the Link, the power flow exchange at the boundary points and the neighbor behavior in contingency and emergency case should be known at every moment. Consequently 3 types of interfaces are defined as follows: Link-Link, Link-Storage and Link-Producer. So, when a Link needs to connect to another Link or other electrical component in order to run, it shall exchange the predefined information by using the appropriate interface. For a better understanding of the new Link architecture the Link types and then the interfaces are discussed in the following.

3.2. Link types

The Link definition is very common, but based on the Link-grid types HVG, MVG, LVG and CPG there are defined four different Link types: a) high voltage link, HVL; b) medium voltage link; MVL; c) low voltage link, LVL and d) customer plant link, CPL. Fig. 4 shows a Link-grid overview and the

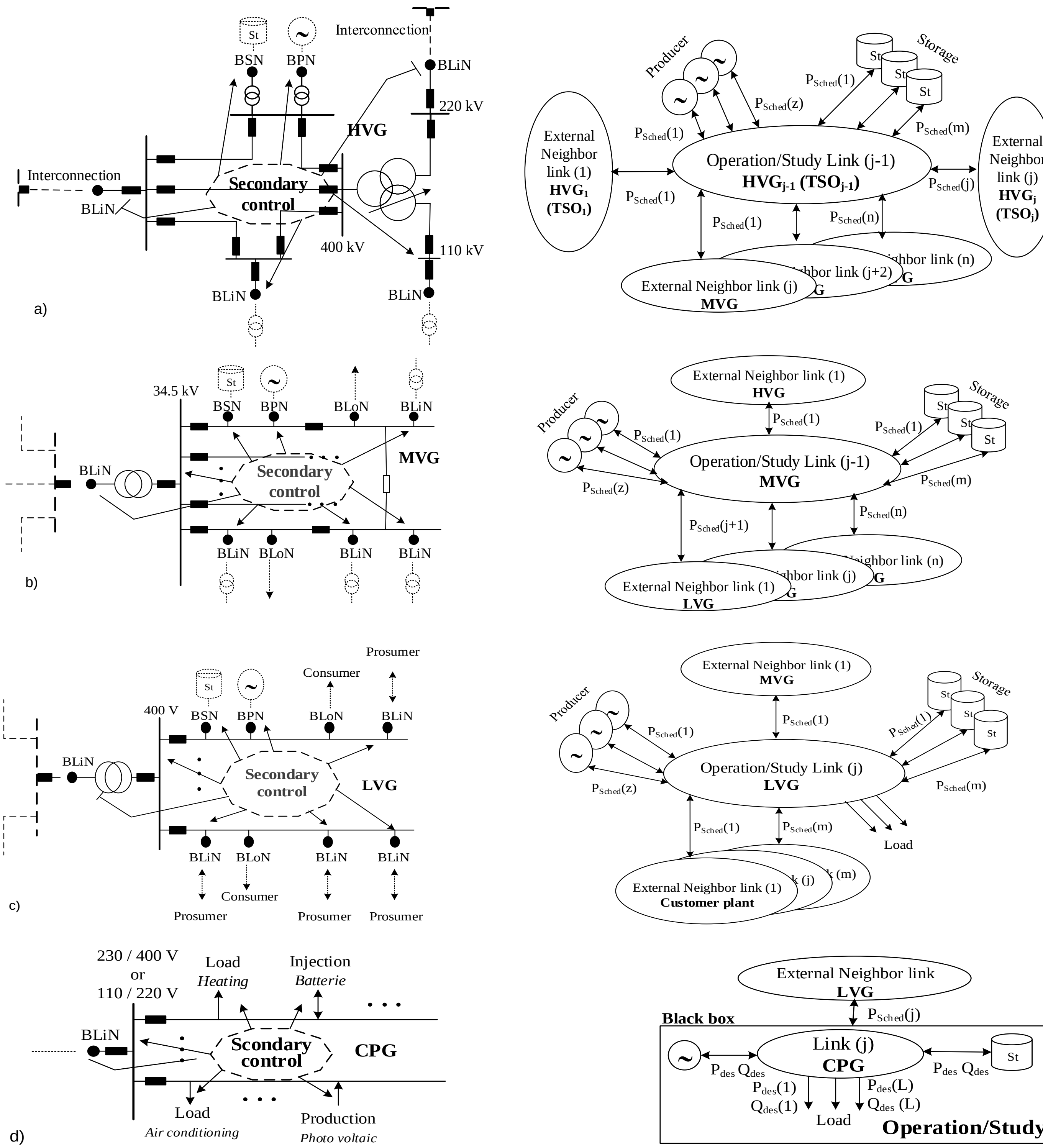

Fig. 4. Link-grid overview and the corresponding entities which should be exchanged in normal operation conditions for different Link types: a) HV-Link; b) MV-Link; c) LV-Link and d) CP-Link

corresponding entities $P_{\mathrm{sched}}(i)$ which should be exchanged in normal operation conditions for different Link types: a) HVL; b) MVL; c) LVL and d) CPL.

a) HVL→ the HVL-grid is meshed and upgraded with redundant real-time measurements, Fig. 4a. The neighbors of this Link are almost other HVLs and MVLs, generators and storages. The relevant interfaces are Link_Link; Link_Generator and Link_Storage. The secondary control area may be the same as the transmission system operation, TSO control area. Special for the European network type the sub transmission network (almost 110 kV) part will create an own Link-grid of the type high voltage, HV.

b) MVL and c) LVL → are normally radial Fig. 4b and 4c. The HVL_Grid have one intersection point with the HVL_Grid over the high voltage / medium voltage, HV/MV transformer. Normally its secondary control area will include only one subsystem, which means only one part of the, distribution system operator, DSO control area. Since the topology is updated almost manually in SCADA (supervisory control and data acquisition), the secondary control area is dynamically changed and in the given case two Links will be automatically merged to one. These Link types differ from each other by the different voltage levels, which have an impact on the electrical parameters of the lines/cables and the availability of the real time measurements. While the MVL has very few real-time measurements, the LVL has actually none.

d) CPL → a pure black box with secondary control over the customer-plant equipment, which has to reach an energetic, economic optimum by fulfilling the agreements/requirements with LVL, Fig. 4d. In contrast to the other Link types this Link is not under the administration of utilities, but of the customer i.e. of the "House Lord".

Each Link or Link-bundle operator (which are described in section 3.4.) is aware of the electricity producing capacity of the facilities feeding into its own grid and its limitations. It conceives the topology with respect to the power producers and consumers and its own ability to distribute the electricity. The Link knows the control response of each of the electricity producers and can issue sequences to meet the dynamic needs of the area. To ensure a feasible, reliable, and resilient operation the relevant information should be exchanged through the interfaces with the neighbor Links, the producer, storage facilities and even customer plants.

3.3. Link interfaces

The exchanged information via these interfaces should enable a secure and reliable operation by means of load generation balance, static and dynamic security, and optimization processes for each Link. The relevant electrical entities to be exchanged for the all three types of interfaces Link_Link, Link_Producer and Link_Storage types are shown in Table 1.

<u>Link_Link_Interface</u>

The Link_Link_Interface is the most extensive one. The day a head $P_{Schedule}^{dayahead} \pm \Delta P$ and next hour schedules $P_{des}^{nexthour} \pm \Delta P$ should be exchanged to enable the load-production balance. ΔP is the active power capacity support (spinning reserve), which each link should provide during contingency conditions. This is also relevant for the (n-1) security calculations. In this case also the available reactive power resources should be known, $Q_{Schedule}^{dayahead} \pm \Delta Q$, $Q_{des}^{nexthour} \pm \Delta Q$. The dynamic data for the equivalent generator and the equivalent exciter, voltage regulator, turbine and the governor should be calculated on real time and exchanged between links to enable the angular and voltage stability calculations. Links can also offer services to each other by means of secondary and tertiary reserve. The frequency f_{meas} is necessary to enable the synchronization process of Link_Grids, which have been operating in island mode. Demand response is the current issue nowadays. The request for load decreasing/increasing is included in the interface in form of the desired instantaneous value, $P_{\mathrm{des}} \pm \Delta P$, $Q_{\mathrm{des}} \pm \Delta Q$. A detailed description of the demand response process is given in the following. Depending on the interfering Link types it can be distinguished between the HVL-HVL_Interface; HVL-MVL_Interface, MVL–LVL_Interface, MVL_

TABLE 1
ELECTRICAL ENTITIES FOR DIFFERENT LINK INTERFACE TYPES

	Electrical entities to be exchanged (*)	Link-Link	Link-Producer_Complex (**)	Link-Storage_Complex
Very fast	f_{meas}	√	√	√
	V_{meas}, δ_{meas}	√	√	√
	P_{meas}, Q_{meas}	√	√	√
	P_{set_point}, Q_{set_point}	√	√	√
Fast	$P_{des}\pm\Delta P$, $Q_{des}\pm\Delta Q$ Delivered time Time interval	√	√	√
	$P_{des}^{nexthour}\pm\Delta P$ $Q_{des}^{nexthour}\pm\Delta Q$	√	√	√
	$P_{Schedule}^{dayahead}\pm\Delta P$ $Q_{Schedule}^{dayahead}\pm\Delta Q$	√	√	√
Slow	Static and dynamic (lumped) load characteristic k_{PV}, k_{QV}, k_{Pf}, k_{Qf} …	√		√
	I_{equiv}, Z_{equiv}	√		
	Dynamic equivalent Generator parameters like x_d, x'_d, …, T'_{d0}, …	√	(***)	
	Equivalent voltage regulator, static exciter parameters like K_A, T_A, …	√	(***)	
	Equivalent governors, turbine parameters like K_1, T_{G1}, …	√	(***)	
	Schedule for demand response capability	√		√
	Reserves schedule (secondary, tertiary)	√	√	√

* data related to the boundary node
** P and Q can have only one sign. Producers only inject power on the grid
*** static data should not be exchanged via interface

and LVL– CPL_Interface.

HVL- HVL_Interface

The HVL-HVL_Interface is the typical interaction between e.g. two TSO areas. Nowadays, one of the crucial functions on HV or rather HVL is the balance load production in real time which is normally realized via the Automatic Generation Control (AGC), [15]. The HVL-grid is practically the grid part included on the AGC controlling area.

AGC is designed to control the real power in commercial bases. While the Link_AGC will perform the scheduled interchange obligations to other interconnected utilities (HVL neighbors) or rather also on MVLs neighbors on technical and commercial bases. The methods to prepare the system for the real time and to perform the load production balance are well known and well established in this voltage level. The HVL is completed when it is upgraded with the Volt/var secondary control.

HVL– MVL_Interface

The HVL–MVL interface is the typical interaction between the HVG and MVG which takes place through the HV/MV supplying transformer. All entities defined for the Link-Link interface should be exchanged to ensure the coexistence of the two Link-types. The existing HVL_Secondary-Control for the frequency / real power should be extended with the exchange over the supplying transformers and should provide the set points P_{set_point} calculated on real time. These set points have to be treated as dynamic constraints from the MVL_Secondary-Control. The same schema should be also used for the voltage / reactive power entities.

MVL - LVL_Interface

The MVL – LVL interface is the typical interaction between the MVG and LVG realized technically through the medium voltage / low voltage, MV/LV distribution transformer. Up to now, from MVG, i.e. MVL_Grid, point of view the LVG, i.e. LVL_Grid, was modelled using the lumped feeder load. Similar as described above also here the MVL_Secondary-Control will send the P_{set_point} and Q_{set_point} to the MVL_secondary-control, which has to treat them as constraints. Here the service restoration is more relevant than the (n-1) security calculation. ΔP and ΔQ will be used for restoration purposes. With the increasing of the DG share, the calculation of the dynamic Link behavior will be also relevant.

LVL-CPL_Interface

The LVL-CPL_Interface is the typical interaction between the LVG i.e. LVL_Grid and the house. The Link is by definition modular and closed in itself, thus fulfilling the data privacy conditions. Different from [27], where certain household appliances should be turned on/off by network operators and energy suppliers, in the new functional architecture the house is a black box for them. The network operator interacts with the houses through the interface, which gives information only about their exchange and their needs ($P_{des}\pm\Delta P$, $Q_{des}\pm\Delta Q$). No any information over the household appliances which are currently in operation is accessible from the grid operator or the energy supplier. The house lord may realize the controlling of the house appliances by using internet, but the communication with the grid should be realized only via safe ways, thus protecting the power delivery systems from the cyber-attacks. The LVL will send the negotiated set points P_{set_point}, Q_{set_point} to the CPL. The real time exchange with the grid will be supervised by the CPL_Secondary-Control. The daily and hourly *P* and *Q* schedules may be generated by a powerful Home Management Unit, HMU, which have to be discussed elsewhere. Theoretically all entities for the Link-Link interface defined in Table 1 will be necessary also for this link combination, but actually and for the near future it is not realistic to collect and prepare this kind of data, because firstly the house electrical grid is not on the utilities nomenclature and practically they do not have access on it. Secondly, also the house lord as owner of the CPL_Grid normally do not have the required information. The developments in many research projects shows that beside the automation, also step-voltage regulators are foreseen to be installed in LV and CP levels. Over time, this trend of development will require more calculations and coordination, and therefore it makes sense to plan this interface with the all data described in Table 1.

3.3.1. Link-Producer_Interface

The Link-Producer_Interface is the typical interaction between the TSOs and the power supplier. This interface is well established in transmission level i.e. between the HVL_Grid and the electricity producer injecting through step up transformers in HVG. The same interface should be used also for the interaction MV- and LVL producer. This interface is not relevant for the CPL because the CPL_Grid and the home electricity producer have the same owner.

3.3.2. Link-Storage_Interface

The Link-Storage_Interface is the typical interaction for ex. between the TSOs and the pumped hydro storage power plants, which are in operation for many years now. Up to now the storage was treated as a part of the generation power plants, because they were not prevalent. However with the new development the number of storage units based on different technologies is increasing continuously. Regardless of that, from the grid point of view they behave identically: they store energy during off-peak times, and then release on request. The entities defined in Table 1 are sufficient to support this behavior and are relevant for all link types HV-, MV-, and LVL. This kind of interface is not relevant for the CPL because the CPL_Grid and the home electricity storage units, potentially batteries of electrical cars, have the same owner.

3.4. Link operation

In [25] is foreseen an own operator for each Link or Link-bundle type. CPL is a special one, because the owner is the House Lord who normally isn't aware about it. Therefore the reliable active operation of this Link type can be realized only if it is fully automated.

Fig. 5 shows the composition of the system / Link operators for different Link types. Actually there do exist two types of systems operators:

1. The TSO or Independent Systems Operator respectively (ISO) for the European and North American respectively, who are responsible for the operation of the transmission grid;

2. The DSO is responsible for the distribution grid. The DSOs for the North American type of distribution grid are responsible for the primary and secondary grid [28], while for the European ones are usually responsible for the sub-transmission, and the MV and LV grid.

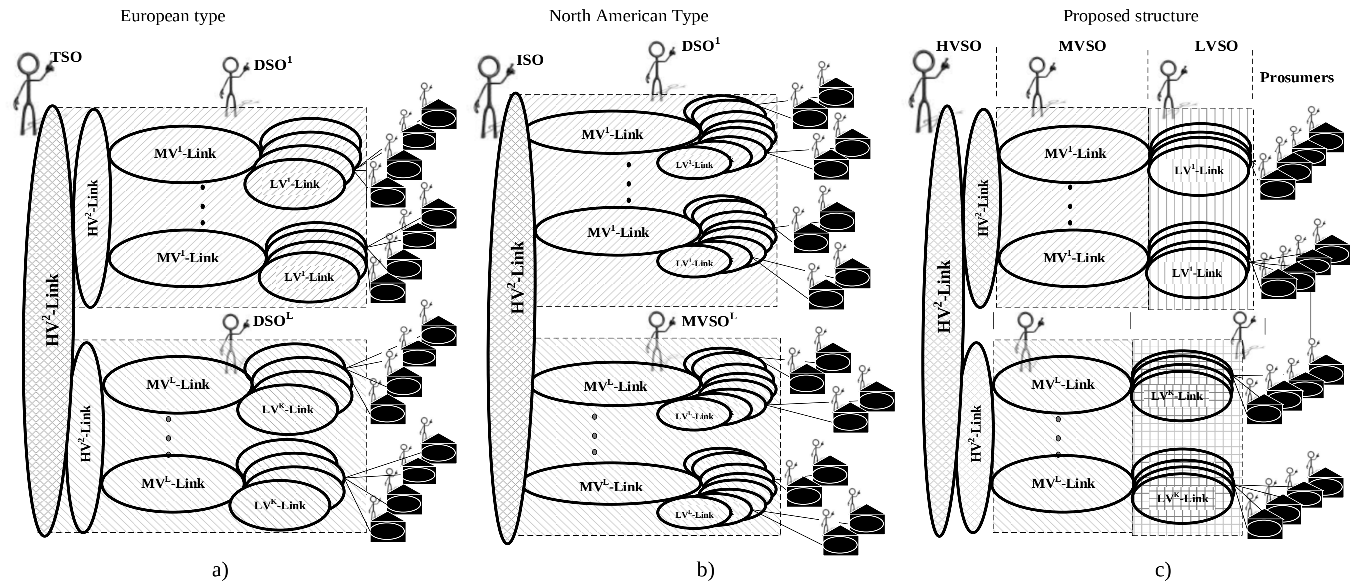

Fig. 5. System operators for different Link and grid types

Fig. 5a and 5b show the operating areas defined in [25] by maintaining the existing structures. In the European type of grid, the TSO is responsible for the operation of the HVL, while the DSO is responsible for the conglomerate of the link types as follows: HV_, MV_ and LV-Link types, Fig. 5a. In the North American grid type, the ISO is responsible for the operation of the HVL, while the DSO is responsible for the MV_ and LVL type, Fig. 5b. Fig. 5c, shows the proposed structure in the context of [25], which provides the unbundling of the distribution operation on: the operation of medium/primary and low/secondary voltage grid i.e. MV_ and LVL-operation. In this case the power grid will be operated from three types of operators: High-, Medium- and Low Voltage System Operators (HVSO, MVSO and LVSO) which are responsible for the operation of the HVL, MVL and LVL respectively.

Each Link or Link-bundle operator be HVSO, MVSO, and LVSO including even the House-Lord (more exactly the HMU) should:

- balance the load and the injection in real-time, where the load represent the summation of the system native load and the scheduled exchange to other Links, while the injection represent the summation of the generation, injection from storage devices and the scheduled exchange to other Links.
- actively manage its Link or the Link-bundle
- monitor its Link-grid or the bundle of Link-grid
- access all the data of the Link
- exchange the data with the neighbor Links and all devices connected directly to the own Link-grid or to the bundle of Link-grid
- have the right to use and offer services to the neighbors
- have the right to dispute with the neighbors to guarantee a reliable and stable operation of his own Link_Grid
- decide the actions should be taken for a secure and optimal operation of the own Link or Link-bundle
- be incentivized to invest in adequate solutions, beyond physical reinforcements, to increase the flexibility of the Link or Link-bundle
- to facilitate effective and well-functioning retail markets

4. Power System Posturing

The functionality of the upgraded architecture is demonstrated by means of two power systems posturing processes: demand response and dynamic security process.

4.2. Demand response process

Fig. 6 shows the demand response [29] process when an HV-line is overloaded. HVSO identifies a lightly overloaded line, where next hour is expected an increase in the overload up to 8%. By using the relevant applications he defines the boundary nodes A^H and B^H on its grid where the load decrease should be performed with an amount of 2 and 6% respectively. Both links connected on the boundary nodes are MVLs and are operated from the same operator MVSO_A. Afterwards, HVSO initiates a demand decrease request and proposes 2 new set points, which are accompanied by the setting and duration time.

After receiving the request for the new set points, MVSO_A investigates all possibilities to realize the demand decrease by using their own resources ex. the Conservation Voltage Reduction [30, 31], CVR. The 2% reduction of the power which is injected through the boundary node A^H into the MVL_1 can be realized by performing the CVR on it. No other actions are needed. The new set point is notified to the HVSO.

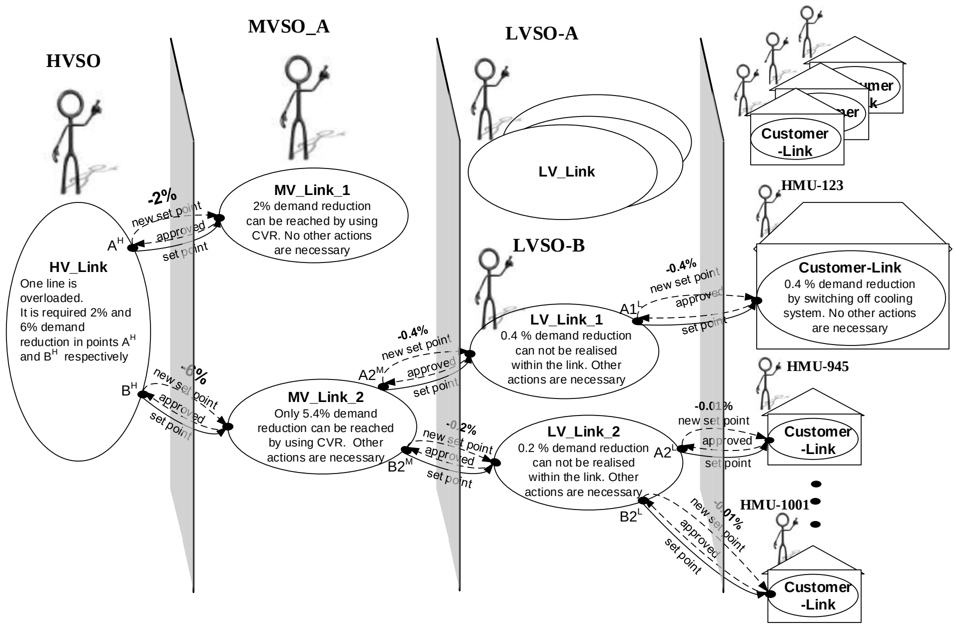

Fig. 6. Demand response process: line overload on high voltage grid

The reduction desired on the boundary node B^H is bigger than at A^H, about 6%, and only one part of it, e.g. 5.4%, can be reached by performing CVR in MVL_2. For the rest, about 0.6% demand reduction, other actions are necessary. After investigating his own network and the day-1 schedules, MVSO_A identifies the boundary nodes $A2^M$ and $B2^M$ as the most suitable ones, which should bring a reduction of 0.4 and 0.2% respectively. LVL_1 and LVL_2 are connected respectively to the boundary nodes $A2^M$ and $B2^M$. Both links are operated from the LVSO_B. Afterwards, MVSO_A initiates a demand decrease request and proposes 2 new set points, which are accompanied by the setting and duration time.

After receiving the request for the new set points, LVSO_B investigates all possibilities to realize the demand decrease. He cannot perform the CVR in its own Link_Grids and therefore he should pass over the request on to the customers, who already have signed a contract for participation in "demand response" process. After performing its own calculations LVSO_B finds three boundary nodes which are most suitable to realize the demand reduction: $A1^L$ in LVL_1 and $A2^L$ and $B2^L$ in LVL2. Consequently, LVSO-B initiates a demand decrease request and gives over the amount of load decrease, 0.4%, 0.01% and 0.01% respectively. The request is accompanied by the setting and duration time of the new set points.

HMU-123 is connected to the boundary node $A1^L$. After receiving the request for the new set point, HMU-123 investigates all possibilities to realize the demand decrease. He approve the new set point and notify LVSO-B. The same approval and notifying procedure is used also by HMU-945 and HMU-1001.

After collecting all replies LVSO-B approve the new set points for the boundary nodes $A2^M$ and $B2^M$

and notify MVSO_A.

Having the approvals from both relevant boundary nodes MVSO_A can fulfill the requirements in the boundary node B^H, approves the new set point and notify the HVSO.

HVSO sent the ultimate set points accompanied by the setting and the duration time. MVSO_A makes the final changes on the set point schedules and sent the information further to LVSO-B who repeat the same procedure as MVSO_A. HMUs act similarly.

Thus, by supervising and controlling the fluxes at the boundary nodes the Link_Secondary Control enables the cross demand response by all voltage level grids up to the native load.

4.3. Dynamic security process

Fig. 7 shows the dynamic security process for the HVL when a new DG is switched-on on the grid of the MVL_2. Although the DG is not part of the MVL_2, it impacts its dynamic behavior. Therefore the new parameters [32] for the dynamic equivalent generator DEG^{new} and the equivalent impedance EI^{new} related to the B^M will be calculated on line. The new calculated values will be committed to the HVL (BLiN, B^H) if they are different from the old ones, Fig. 7a. Thus the HVL is notified that one of the neighbors has changed the dynamic behavior. For this reason HVL will initiate the calculation of the dynamic stability (angular and voltage) of its own Link with the updated parameters on the calculation model, Fig. 7b.

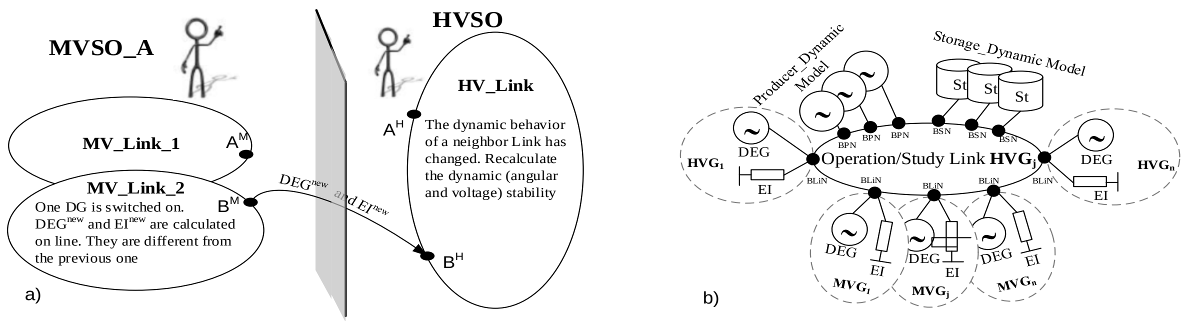

Fig. 7. Dynamic security process for the HV_Link: a) Interlink information exchange; b) Calculation model

5. ICT architecture

The technical-functional architecture presented above is facilitated by the global component base ICT architecture. Fig. 8. Each Link type be HV, MV and MV has its own multi computer system, i.e. a Control Center: HV-CC, MV-CC and LV-CC. HV-CC normally operates one HV_Link, while MV_CC and LC_CC operate a bundle of MV_ or LVLs. The bidirectional communication paths between them are shown with arrows. The communication is done in a certain sequence. HV_CC can directly communicate

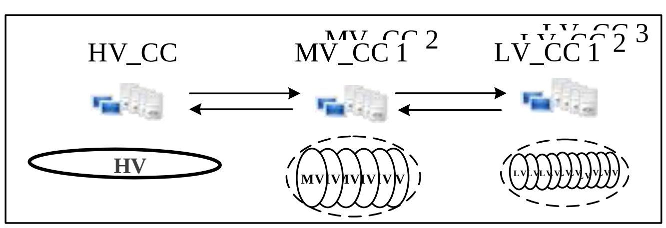

Fig. 8. Power system global component base IT architecture

only with the MV_CC, but not with LV_CC. MV_CC can communicate directly with HV_CC and LV_CC. While, LV_CC can communicate directly only with MV_CC, but not with HV_CC. The relevant communication interfaces are already defined in Table 1.

6. Market Accommodation

As mentioned above one of the roles of the link operator is to facilitate effective and well-functioning retail markets. Fig. 9 shows the accommodation of the different link operators as market actors. All energy producers should trade their production into the market. The trading market is already established for all large energy producers. While customer facilities and small distributed energy producers can go into the market through the well-known model of Commercial Virtual Power Plant, [33]. In addition, they have to coordinate the operation between each other based on contractual arrangements at a technical and economical level. Thus the HVSO should establish contractual arrangements at both levels, technical and economical, with the MVSO. Similarly MVSO should establish contractual arrangements with HVSO and LVSO at the both levels too [25].

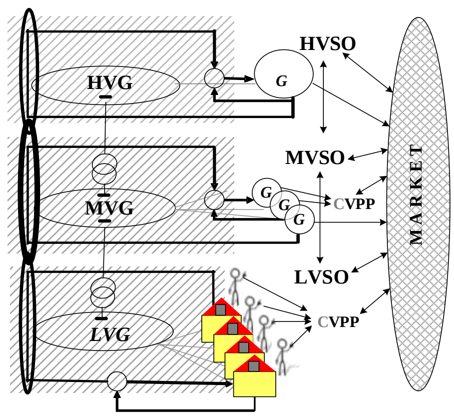

Fig. 9. The accommodation of the different link operators as market actors

7. Implementation

The proof of the concept is done in the frame of the industrial research project ZUQDE (Central Volt/var Control in presence of decentralized generation), Salzburg, Austria, [25, 34] for one of the major entities of power systems, the voltage. There the MVL was realized, where the Link_Secondary-Control was realized by means of the Volt/var control, Fig. 10. Its algorithm has calculated the set points by respecting the constraint. The constraint was set to the HV/MV transformer by means of a constant cosϕ. The set points were sent to all four "run of river" distributed generators by means of the reactive power Q, while to the feeder head bus bar was sent the voltage set point. All relevant generators were upgraded with the primary control, thus building up the Producer component. All distributed transformer were modelled as loads. As result, the voltage in Lungau region was automatically controlled and at once the grid was being dynamically optimized in real-time for more than one year.

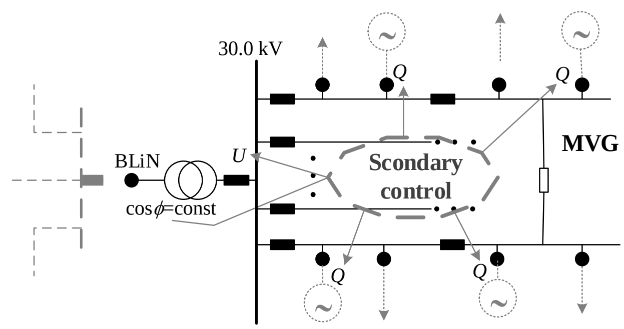

Fig. 10. MVL realized and operated in the framework of ZUQDE project

8. Transition period

The upgrade of the power system architecture is compelling, but won't be built in a day – or a decade. Consequently, the upgrade process will be accompanied by a transition period with a mixed architecture. During all this time, the upgrade should be done stepwise to ensure a secure, reliable and feasible operation of the entire power system. The most important upgrade steps are presented in the following.

HVG and the power plants which are feeding to it, are the backbone of the power system which is responsible to supply the electricity with a predefined frequency and voltage. Consequently, the consolidation of the Volt/var loop in MVL with well-defined constraints on the boundary with the HVL have the highest priority [35]. After this the HVL and the LVL may be consolidated simultaneously. The consolidation of the loops concerning active power / frequency should follow the reactive power / voltage ones.

9. Exchanged data minimization

One of the main goals of the architecture described in this paper is the minimization of the exchanged data. To show this, we selected the case of exchanging the scheduled data and compared the data exchange amount needed by the centralized vs. decentralized architecture.

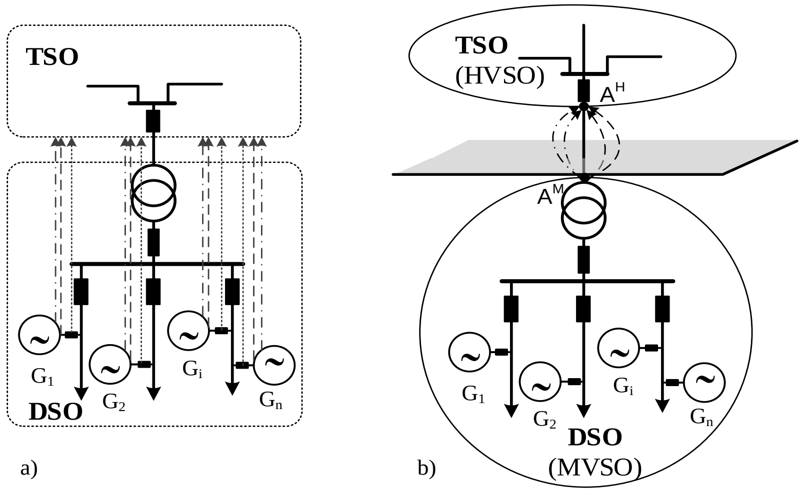

Fig. 11. The scheduled data exchange on two different architectures: a) centralized and b) decentralized.

The centralized power system architecture proposed in [12, 13] should take over the attribution of a super management system, that observes, controls and manages transmission and distribution network together. It requires the integration of TSO and DSOs and a new communication system, which should encompass the entire infrastructure. Based on [36] Article 25, each significant distributed generator shall provide three kind of schedules: 1) the scheduled unavailability; 2) the forecasted scheduled active output at the connection point in distribution grid and 3) any forecasted restriction in the reactive power control capability. Fig. 11 shows the scheduled data exchange between the TSO and the owners of the significant distributed generators based on two different architectures. There are n significant distributed generators connected on the MVG-part that have only one connection point with the HVG. Fig. 11.a) shows the data should be changed in the case of the centralized architecture. The number of the data should be exchanged in this case is $3 \cdot n$. Fig. 11.b) shows the data should be changed in the case of the decentralized architecture. Under this architecture the owners of the generator should exchange the data only with the operator of the Link where they are connected. Due to the enclosed nature of the links, the TSO should get any information about the network users, who are directly connected to the distribution network. That means they should communicate only with the DSO (MVSO). The TSO will receive the required scheduled data from the DSO (MVSO). The exchanged data are the day a head scheduled active and reactive power and the corresponding active and reactive power support ($P_{Schedule}^{dayahead} \pm \Delta P, Q_{Schedule}^{dayahead} \pm \Delta Q$), that flow in the intersection point HV/MV; $A^H A^M$. The number of the data should be exchanged is 4. As result, the scheduled data amount that should be exchanged in the case of the centralized architecture increases continuously by $3 \cdot n$, while in the case of the decentralized architecture it will always remain constant at 4.

10. Conclusion

For the first time is presented the smart grid paradigm: the “Link”. The “Link”-paradigm facilitates the modelling of the complete power system including the customer plants and the description of all smart grid system operation processes. A new architectural framework is proposed which have three main components: the Grid-Link/the Link, the Producer-Link/the Producer and the Storage-Link/the Storage. The entire power grid and the customer plants are presented through only one major, standardized component: the Link. The distributed Link-based architecture reduces in a minimum the number of exchanged data and enables a secure, reliable and sustainable operation in normal and emergency cases. The Link based architecture enables the market to flourish and motivate consumers to actively participate in operation of the grid by maintaining their privacy.

11. Acknowledgments

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